

An Efficient Method for Speed Control of DC Shunt Motor using Response Surface Methodology (RSM) Approach

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Abstract—The fundamental equations governing the operation of a dc motor are straightforward and are well presented in most undergraduate curricula, usually in a required energy-conversion or electrical-machinery class at the junior level. The physical implications of the equations regarding device behaviour, and the need for speed control, are easily understood. The present research work deals with the application of Response Surface Methodology (RSM) for controlling as well as estimating the rotating speed of a DC shunt motor. As the rotating speed of DC shunt motor depends on armature voltage and field current applied to the shunt motor, therefore, these two process parameters were varied during experimentation. Central composite design of experiments based experimental designed has been applied and 13 number of experiments have been performed. Moreover, empirical model has been developed to predict any desired speed of rotation of the DC shunt motor and the model has been validated through confirmation experimentations. The present paper will be useful for the students to readily draw a mental picture regarding the rotating speed of the shunt motor and applied voltage and current. The response surface method has been successfully applied to overcome the speed-control problem.

Keywords— DC shunt motor, Speed control, Response surface methodology, Computational intelligence.

I. INTRODUCTION

A shunt motor has slightly different operating characteristics than a series motor. Since the shunt field coil is made of fine wire, it cannot produce the large current for starting like the series field. This means that the shunt motor has very low starting torque, which requires that the shaft load be rather small. When voltage is applied to the motor, the high resistance of the shunt coil keeps the overall current to flow at low value. The armature for the shunt motor is similar to the series motor and it will draw a current to produce a magnetic field strong enough to cause the armature shaft and load to start turning. Like the series motor, when the armature begins to turn, it will produce back electro-magnetic force (EMF). This back EMF will cause the current in the armature to begin to diminish to a very small level. The amount of current that the armature will draw is directly related to the dimension of the load when the motor reaches its full speed. Since the load is generally small, the armature current will be small. Whenever

the motor reaches its full rpm, its speed will remain fairly constant.

The shunt motor's speed can be varied in two different ways. These include varying the amount of current supplied to the shunt field and controlling the amount of current supplied to the armature. Controlling the current to the shunt field allows the rotating speed to be changed at 10-20% when the motor is at full rotational speed. This type of speed control regulation is accomplished by slightly increasing or decreasing the voltage applied to the field. The armature continues to have full voltage applied to it while the current to the shunt field is regulated by a rheostat that is connected in series with the shunt field. When the shunt field's current is decreased, the motor's rpm will increase slightly. When the shunt field's current is reduced, the armature must rotate faster to produce the same amount of back EMF to keep the load turning. If the shunt field current is increased slightly, the armature can rotate at lower rpm and maintain the amount of back EMF to produce the armature current to drive the load. The field current can be adjusted with a field rheostat or an silicon control rectifier (SCR) current control. The shunt motor's rpm can also be controlled by regulating the voltage that is applied to the motor armature. This means if the motor is operated on less voltage than is shown on its data plate rating, it will run at less than its full rpm. You must remember that the shunt motor's efficiency will drop off drastically when it is operated below its rated voltage. The motor will tend to overheat when it is operated below full voltage, so motor ventilation must be provided. The motor's torque is reduced when it is operated below the full voltage level. Since the armature draws more current than the shunt field, the control resistors were much larger than those used for the field rheostat.

Generally, the rotational speed of a DC motor is proportional to the voltage applied to it, and the torque is proportional to the current. Speed control can be achieved by variable battery tapings, variable supply voltage, resistors or electronic controls. The direction of a wound field DC motor can be changed by reversing either the field or armature connections but not both. This is commonly done with a special set of contactors (direction contactors). The effective voltage can be varied by inserting a series resistor or by an

electronically controlled switching device made of thyristors, transistors, or, formerly, mercury arc rectifiers.

During the last 25 years, there have been significant developments in methods for model based control [1]-[2]. A recent survey of evolutionary algorithms for evaluation of improved learning algorithm, control system can be found in [3]-[4]. Among the techniques found out, intelligent techniques and computational optimization techniques have found themselves a place in tuning of the parameters. The intelligent techniques like artificial neural networks (ANN), fuzzy logic (FL) have been developed over the last ten years [5]-[6]. Neural and fuzzy logic mimic the functioning of human intelligence process [7]. But their real time implementation is quite difficult [8]. Hence as a result of the above said problems optimization algorithms have received increasing attention by research community [9]. In recent years, there have extensive research on heuristic stochastic search techniques for optimization of the PID gains [10]-[11]. An optimization algorithm is a numerical method or algorithm for finding the maxima or the minima of a function operating with certain constraints [12]. An optimal control is a set of differential equations describing the paths of the control variables that minimize the cost function [13]-[14]. Computational intelligence was the way in which optimization was done. Computational intelligence (CI) is a successor of artificial intelligence relying on evolutionary computation, which is a famous optimization technique. Computational intelligence (CI) combines elements of learning; adaptation and evolution to create programs that are, in some sense, intelligent. Computational intelligence research does not reject statistical methods, but often gives a complementary view [15]. The importance of CI lies in the fact that these techniques often find optima in complicated optimization problems more quickly than the traditional optimization methods [16]. Simulated annealing (SA) is a derivative-free stochastic search method for determining the optimum solution in an optimization problem. The method was proposed by Kirkpatrick in 1983 and has since been used extensively to solve large-scale problems of combinatorial optimization. The SA evolves a single solution in the parameter space with certain guiding principles that imitate the random behaviour of molecules during annealing process. It is similar to the physical process of heating up a solid until it melts, followed by cooling it down slowly until it crystallizes into a perfect lattice. The objective function here corresponds to the energy of the states of a solid [17]. The SA algorithm requires the definition of the neighbourhood structure as well as the parameters for the cooling schedule. The temperature parameter distinguishes between large and small changes in the objective function. An attractive feature of SA is that it is very easy to program and the algorithm typically has few parameters that require tuning. In the proposed work response surface method has been introduced to control the rotational speed of DC shunt motor statistically by varying the armature voltage and field current applied to it. There is a problem faced by experimenters in many technical fields, where, in general, the response variable of interest is y and there is a set of predictor variables x_1, x_2, \dots, x_k . For example, in Dynamic Network Analysis (DNA) Response Surface Methodology (RSM) might be useful for sensitivity analysis of various DNA measures for different kinds of random graphs

and errors. In social network problems usually the underlying mechanism is not fully understood, and the experimenter must approximate the unknown function g with appropriate empirical model

$$Y = f(x_1, x_2, \dots, x_k) + \varepsilon \quad (1)$$

where, the term ε represents the error in the system. Usually the function f is a first-order or second-order polynomial. This empirical model is called a response surface model. Identifying and fitting from experimental data an appropriate response surface model requires some use of statistical experimental design fundamentals, regression modeling techniques, and optimization methods. All three of these topics are usually combined into Response Surface Methodology (RSM).

Also the experimenter may encounter situations where the full model may not be appropriate. Then variable selection or model-building techniques may be used to identify the best subset of regressors to include in a regression model. In our approach we use the simulated annealing method of optimization for searching the best subset of regressors. In some response surface experiments, there can be one or more near-linear dependences among regressor variables in the model. Regression model builders refer to this as multicollinearity among the regressors. Multicollinearity can have serious effects on the estimates of the model parameters and on the general applicability of the final model. The RSM is also extremely useful as an automated tool for model calibration and validation especially for modern computational multi-agent large-scale social-networks systems that are becoming heavily used in modeling and simulation of complex social networks. The RSM can be integrated in many large-scale simulation systems such as BioWar, ORA and is currently integrating in Vista, Construct, and DyNet.

II. PROBLEM DEFINITION

The rotating of a DC shunt motor depends on the armature voltage and field current applied to the particular motor. In the present paper, an attempt has been taken to achieve the desired speed of a DC shunt motor by varying these two process parameters such as armature voltage and field current. A statistical method i.e. response surface methodology (RSM) has been applied to construct the design of experiments (DOE). The experiments have been conducted on different set of process parametric settings and for each experiment, rotating speed of the DC shunt motor have been noted with the help of a Tachometer. The results of rotating speed were analysed in a statistical software i.e. MINITABTM version 15.0. A model has been developed which can be used to achieve any particular rotating speed of DC shunt motor. The developed model has been validated with another set of confirmation experiments.

III. EXPERIMENTAL APPROACH

The present experimentations have been carried out using an experimental set-up which includes number of apparatus such as DC shunt motor, two variable resistors, one DC ammeter, one DC voltmeter, tachometer etc. Table 1 shows the list of instruments used with their detailed specifications. In Fig. 1, the schematic representation of the detailed connections of the instruments is shown. The photographic view of the set-up

with various instruments connected with the DC shunt motor is shown in Fig. 2. It is evident that the rotating speed of a DC shunt motor depends on armature voltage and field current applied to the shunt motor. Therefore, in the present experiments, these two process parameters were varied keeping other parameter as constant.

TABLE I DETAILS OF INSTRUMENTS USED DURING EXPERIMENTS

Name of instrument	Specifications
DC Shunt Motor	Type: DC 112.178.302 Volt: 220 V, Amp.: 12 A HP: 3.0, RPM: 1500
Variable Rheostat (Vh) Vh 1 Vh 2	360 Ω , 1.1 Amp 50 Ω , 3.3 Amp
Ammeter	0 – 1 Amp
Voltmeter	0 – 300 V
Tachometer	Range: 0-2000 RPM

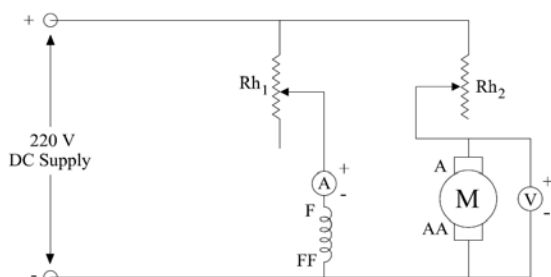


Fig. 1 Schematic diagram of connections for the instruments used

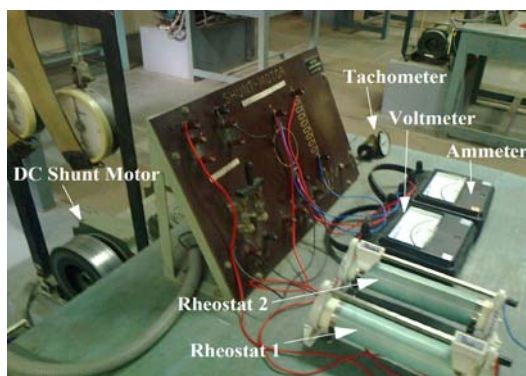


Fig. 2 Photographic view of the experimental set-up with various instruments connected

TABLE II FACTORS AND LEVELS OF PROCESS PARAMETERS CONSIDERED FOR EXPERIMENTATIONS

Parameters	Levels				
	-1.414	-1	0	+1	+1.414
Armature Voltage (Volts)	180	185	190	195	200
Field Current (Amps)	0.3	0.35	0.40	0.45	0.50

Response surface methodology (RSM) based approach has been considered to construct the design of experiments (DOE). Experiments have been carried out based on central composite rotatable second-order rotatable design (CCRD) experimental plan [18]. The considered range of these two process parameters with coded and uncoded levels are enlisted in Table 2. The ranges and the levels of the process parameters have been selected after conducting lot of trial experiments using the machine set-up. The second-order polynomial response surface empirical model can be represented as:

$$Y_u = \beta_0 + \sum_{i=1}^n \beta_i X_{iu} + \sum_{i=1}^n \beta_{ii} X_{iu}^2 + \sum_{i < j}^n \beta_{ij} X_{iu} X_{ju} + e_u \quad (2)$$

where, Y_u represents the corresponding response and the X_{iu} are coded values of the i th process parameters. The terms β_0 , β_i , β_{ii} and β_{ij} are the regression coefficients and the residual, e_u measures the experimental error of the u th observations. According to the design based on response surface methodology, it was observed that there are 13 numbers of experiments for two process parameters and five level values of each of the parameters. Table 3 shows the details of the experimental settings of all those experiments. Each experiment was conducted three times and the average value of the three rotating speeds of the DC shunt motor was calculated. The results of the rotating speed measured during experimentations were analyzed in a statistical software i.e. MINITABTM. Based on the results of rotating speed, a mathematical model has been developed which can be utilized to achieve any desired rotating speed of the DC shunt motor.

TABLE III PARAMETRIC SETTINGS AND CORRESPONDING EXPERIMENTAL RESULTS

Expt. No.	Coded values of parameters		Response
	Armature Voltage	Field Current	Shunt Motor Speed (rpm)
1	0	1.414	1380
2	1.414	0	1575
3	1	-1	1610
4	0	0	1500
5	0	0	1500
6	0	-1.414	1650
7	-1.414	0	1460
8	0	0	1500
9	-1	1	1390
10	-1	-1	1540
11	0	0	1500
12	0	0	1500
13	1	1	1450

TABLE IV RESULTS OF ANALYSIS OF VARIANCE (ANOVA)

Source	DF	Adj SS	Adj MS	F
Regression	5	70711.0	14142.2	66.83
Linear	2	70534.3	35267.1	166.65
Square	2	151.7	75.8	0.36
Interaction	1	25.0	25.0	0.12
Residual Error	7	1481.3	211.6	
Lack-of-Fit	3	1481.3	493.8	2.33
Pure Error	4	0.0	0.0	
Total	12	72192.3		

IV. DEVELOPMENT AND VALIDATION OF THE EMPIRICAL MODEL

Mathematical model based on the results of the rotating speed of DC shunt motor have been developed using MINITABTM software. This model is a second order polynomial equation, which correlates the rotating speed of the DC shunt motor and the two process parameters i.e. armature voltage and field current. The regression equation is as follows:

$$Y_{\text{SPEED}} = 1500 + 36.5793 \times (x_1) - 86.4797 \times (x_2) + 4.06250 \times (x_1)^2 + 2.81250 \times (x_2)^2 - 2.5000 \times (x_1) \times (x_2) \quad (3)$$

Here, YSPEED represents the rotating speed of the DC shunt motor and x_1 and x_2 represent the considered process parameters as shown in Table 2. Analysis of variance (ANOVA) has been conducted to check the adequacy of the developed model of rotating speed of DC shunt motor. The results of the ANOVA test of the present experimentation are shown in Table 4. The tabulated value of F distribution for lack-of-fit is 9.28 at 95% confidence level. However, the calculated F-value for the rotating speed of DC shunt motor is 2.33, which are lower than the standard F value. This implies that the developed empirical model for rotating speed of DC shunt motor is adequate at 95% confidence level. Moreover, as the F values of regression and linear terms are very high than the value of lack-of-fit, so these terms are most significant for the developed model. In Fig. 3, the normal probability plot for the residuals of the achieved rotating speed of the DC shunt motor is shown. Fig. 4 shows the plot between residual versus fitted value and by observing closely these two plots it can be concluded that the developed model estimates satisfactorily.

Based on the developed mathematical empirical model, 4 verification experiments were performed by selecting the process parameters within the range chosen for this experimental study. The experimental and RSM model predicted results along with the percentage error are listed in Table 5. The percentage errors have been calculated according the follows equation.

$$\text{Prediction error} = \frac{\text{Experimental result} - \text{RSM estimated result}}{\text{Experimental result}} \quad (4)$$

It is observed from Table 5 that the experimental results of rotating speed of the shunt motor are close to the RSM generated results and the average percentage errors of prediction for the rotating speed of DC shunt motor are very less ($\leq 0.01\%$). It was also observed that average percentage error is 0.0018%, which is within acceptable range. Therefore, it is concluded that the developed RSM model can be used to estimate the rotating speed of the DC shunt motor quite satisfactorily.

V. RESULTS AND DISCUSSION

The influence of varying the considered process parameters i.e. armature voltage and field current on rotating speed of DC shunt motor has been investigated using response surface obtained from the MINITABTM software. Fig. 5 shows the surface plot of rotating speed for simultaneously variation of the armature voltage and field current in the considered range. Moreover, the main effect plot of the rotating speed of the DC shunt motor for variation of these mentioned process

parameters is shown in Fig. 6. It is observed from both Figs. 5 and 6 that with the increase of armature voltage keeping field current as constant, the rotating speed of the DC shunt motor increases. The relation of rotating speed of the DC shunt motor with armature voltage is as follows:

$$\text{Rotating speed } (N) = \frac{K \times (V - I \times R)}{\phi} \quad (5)$$

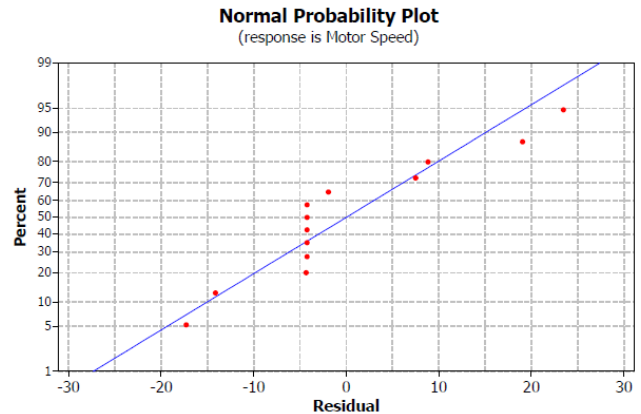


Fig. 3 Normal probability plot of rotating speed of DC shunt motor

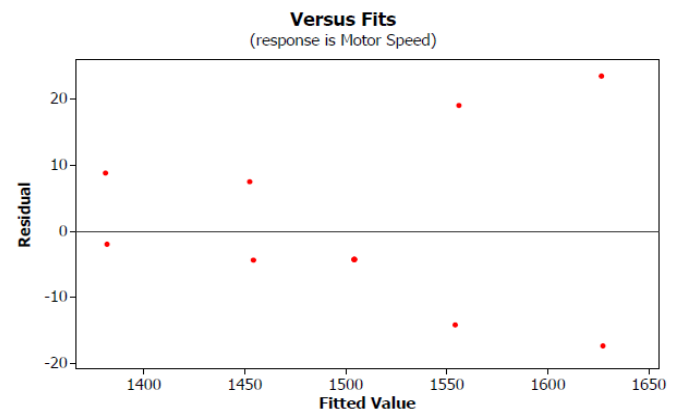


Fig. 4 Residual vs fits of the results of rotating speed of DC shunt motor

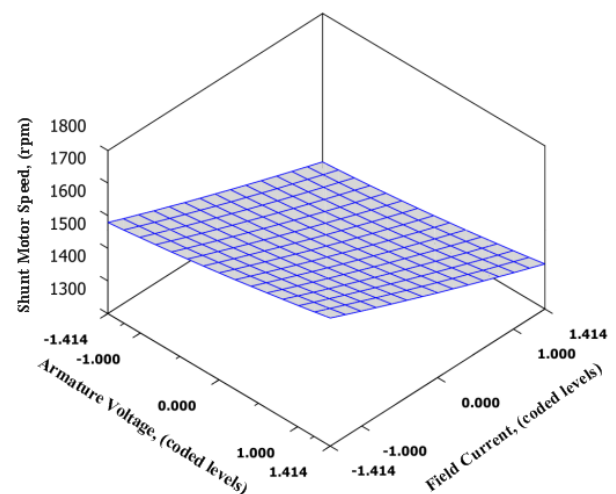


Fig. 5 Surface plot of variation of armature voltage and field current on shunt motor speed

TABLE V VALIDATION EXPERIMENTATION OF DEVELOPED EMPIRICAL MODEL BASED ON RSM

Expt. No.	Coded values of Process Parameters		Shunt Motor Speed (rpm)		Percentage of Error (%)
	Armature Voltage	Field Current	RSM Generated Results	Experimental Results	
1	-1.1	0.9	1391	1394	0.002
2	1	-1.414	1672	1676	0.002
3	0.6	-1	1614	1616	0.001
4	1.414	-0.8	1633	1637	0.002
Average Percentage of Error					0.0018

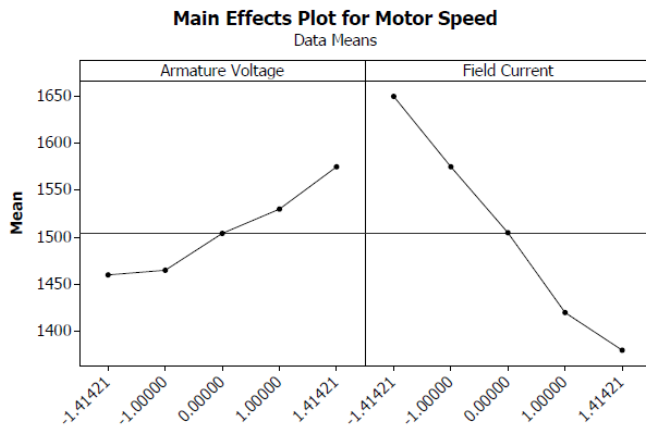


Fig. 6 Main effect plot of rotating speed of DC shunt motor for varying armature voltage and field current

where K , V , I , R and ϕ denote proportional constant, electromotive force (armature voltage in volts), field current (amps), armature resistance (ohms) and flux (webers), respectively. It is obvious from equation (5) that while keeping the other factors as constant; the increase of armature voltage has direct effect on the rotating speed of the DC shunt motor. Moreover, it is also evident from the surface plot that while increasing the field current applied to the motor, it is observed that the rotating speed of the shunt motor is decreased in the considered range of process parameters. According to the equation (5), if the value of the field current is increased, then it has inverse effect on rotational speed of the shunt motor.

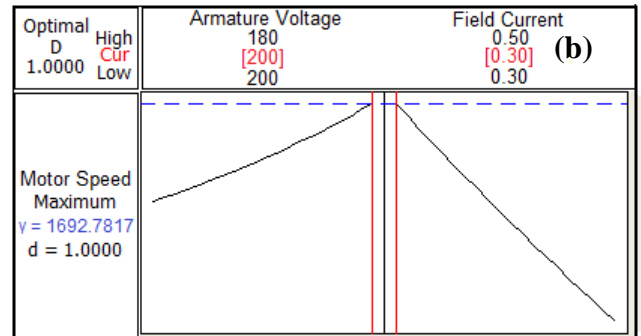
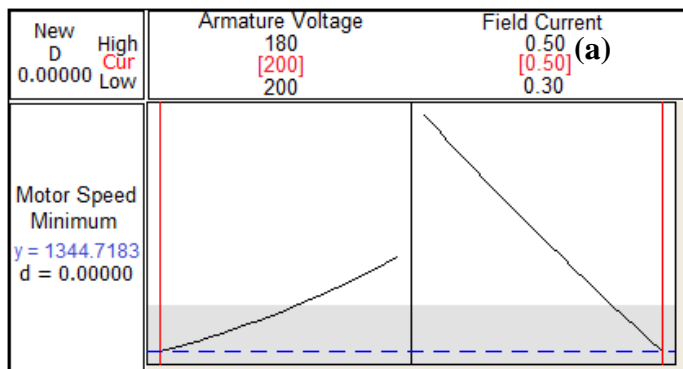


Fig. 7 Pictorial representations for (a) maximum and (b) minimum speed of DC shunt motor achieved from MINITAB™ software

The developed RSM model can be used satisfactorily for achieving any desired speed of the DC shunt motor within a range of 1344.7 (minimum speed) to 1692.7 rpm (maximum speed).

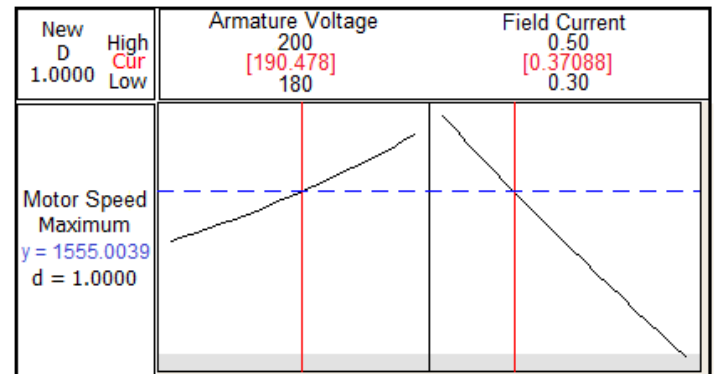


Fig. 8 Pictorial representation of MINITAB™ generated plot for DC shunt motor speed of 1555 rpm

Figs. 7 (a) and (b) show the pictorial view of the MINITAB™ software window that represent the results of minimum and maximum rotating speed of the DC shunt motor that could be achieved for the two process parametric settings i.e. 180volts/0.30amps and 200volts/0.50amps of armature voltage and field current, respectively. Within this range of minimum and maximum speed of rotation, if any particular rotating speed is to be obtained, then the developed RSM model can be used to estimate the setting of the process parameters i.e. the values of armature voltage and field current. For example, if a desired

TABLE VI EXPERIMENTATION FOR ACHIEVING A ROTATING SPEED OF 1555 RPM OF THE DC SHUNT MOTOR

Trials	Process Parameters		Shunt Motor Speed (rpm)		Percentage of Error (%)
			RSM Generated Results	Experimental Results	
	Armature Voltage, volts	Field Current, amps			
1	190.5	0.37	1555	1557	0.001
2				1556	0
3				1557	0.001
Average Percentage of Error					0.001

rotating speed of the DC shunt motor is to be obtained as 1555 rpm, then from the empirical model developed, one can easily estimate the process parametric setting which can result the desired rotating speed of the DC shunt motor. The MINITABTM software generated plot for achieving a particular rotating speed of 1555 rpm is shown in Fig. 8. This desired rotating speed of the DC shunt motor is achieved at process parametric setting of 190.478volts/0.37088amps of armature voltage and field current, respectively. Three experiments have also been conducted in this setting of process parameters to check the accuracy of estimation of the developed RSM model. In Table 6, the results of rotating speed of DC shunt motor achieved from developed RSM model as well as experimentally measured data are enlisted. It is observed from this table that RSM model has estimated the process parametric setting precisely (average percentage error is 0.001%) for achieving the desired rotating speed as experimentally obtained speed is almost nearer to the desired speed of rotation of DC shunt motor.

VI. CONCLUSIONS

In the present paper, response surface method (RSM) has been successfully applied to estimate and control the speed of DC shunt motor by varying the armature voltage and field current. The design for the experiments has been planned based on central composite design (CCD) for experiments and the results of rotating speed of DC shunt motor for various set of process parameters were used to develop a RSM model. The adequacy of the developed model was checked through ANOVA test. An empirical model has been developed and the model has been validated with further experimentations. From the results of confirmation experiments, it is revealed that the developed model can estimate the process parametric setting to achieve a desired rotational speed of the DC shunt motor very accurately. A better control of rotating speed of DC shunt motor has been presented with less number of data for achieving the desired speed of rotation. The methodology to accurately control the rotating speed shown in the paper can be used as powerful tool to control various machineries in the shop floor and also useful to the control engineers.

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